An Experimental Study on the Effect of Plastic Waste Powder on the Strength Parameters of Tuff and Bentonite Soils Treated with Cement

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ABSTRACT

This experimental study investigated the effect of plastic waste powder on the strength and swelling behavior of tuff and bentonite soils treated by cement since the plastic powder is highly compressible and does not absorb much water. This study aimed to improve the tuff and bentonite soils used in construction by adding plastic waste powder in various ratios (5, 10, 20, and 25%) and a low cement content (2.5%). Atterberg limit, swelling consolidation, and loading-unloading tests were performed to determine the optimal composition of the mixture. The results demonstrated that as the plastic powder content increases, the liquid limits, swelling pressure, swelling potentials, and duration to swelling peak decrease. This reduction is particularly notable for the soil with the highest swelling potential. Compression and recompression indices increase significantly with the content of plastic powder due to its high compressibility. The findings suggest that plastic powder with low cement can be utilized as a soil modification reinforcement material, but with a content that shouldn't significantly alter the compressibility of the mixture.

Keywords-tuff; bentonite; plastic powder; cement; compressibility; swelling behavior

I. INTRODUCTION

Stabilized soil is a composite soil created by combining and enhancing the qualities of its various components. Soil swelling caused by a change in moisture is known to cause great stress and serious damage to structures. Expansive soils are known to be shrink-swell or swelling soils. Many studies investigated stabilization and strengthening techniques in order to improve the mechanical and geotechnical characteristics of soils in terms of performance and strength [1, 2], density and compaction [3, 4], compressive strength [5, 6], consolidation [7], durability [8], permeability[9], and micro-structure [10]. Soils made of tuff are categorized as clay soils. When dry soil is in contact with water, it undergoes alteration and may swell and then contract after drying. As a result of this phenomenon, there is considerable pressure, which causes the constructions to fracture [11]. Bentonite soils can be improved in terms of mechanical performance by adding polypropylene polymer matrices [12]. These methods include stabilizing the soil with chemical additives, replacing the soil partially, surcharge loading, and controlling compaction. Plastic is a petrochemical product, which today constitutes most of the physical goods of daily life due to its low cost, multiple uses, lightness, and resistance to breaking. This excessive consumption makes it difficult to control and deal with the huge amounts of plastic waste generated. The annual global production of plastic waste is estimated at 2.01 billion tons [13]. Since 9% of this plastic waste is recycled [14], the rest can be found in both marine and terrestrial environments. Plastic waste should be adequately recycled in order to reduce its harmful effects on the environment. The majority of industrial and packaging processes use plastic in a variety of forms such as polyethylene, polycarbonate, low- and high-density polyethylene, polystyrene, polyvinyl chloride, and polypropylene [15-17]. Recently, plastic waste has been used to improve soils, and its effectiveness in improving tuff soils has already been tested [18-21]. As sustainable development principles with consequent economic growth for all is essential, sorting waste helps to preserve the environment by reducing the amount of plastic waste deposited in the nature. By promoting a circular economy based on the reduction, reuse, and recycling of plastic waste, sorted plastic products can be reused and transformed into new raw materials.

This study combined tuff and bentonite soils with plastic waste powder in ratios of 5, 10, 20, and 25% of total soil weight and treated with low cement content. The results in terms of consistency limits, odometer tests, compression, and recompression tests showed that mixing the tuff soil with plastic powder reduces the heave and swelling pressure. Additionally, the reduction in swelling pressure is a little more significant for soils with 10, 20, and 25% plastic powder. The compression and recompression indices increase progressively with the plastic powder content for both soils.

II. EXPERIMENTAL STUDY

A. *Materials and Methods*

1) *Investigated Soils*

Two soil samples were studied. The first soil sample was tuff from the region of Mascara in the northwest of Algeria and the second was bentonite made from the Maghnia quarries in northwestern Algeria. These two soils were subjected to several laboratory tests to determine their properties using the standard procedures approved by AFNOR and ISO standards NF P 94-051, NF P 94-054, NF 94-056, NF P 94-057, and NF P 94-068. Table I shows the properties of the investigated soils.

TABLE I. PROPERTIES OF THE INVESTIGATED SOILS.

Properties	Tuff	Bentonite
Liquid limit (%)	27.5	28
Plastic limit (%)	14	13
Plasticity index (%)	23.19	83
Specific gravity	1.92	2.61
Grains sizes analysis		
Sand (%)	17.3	12.3
Silt (%)	27.4	19.5
Clay (%)	55.3	68.2
Volume of blue VB (cm^3)	5.3	38.6

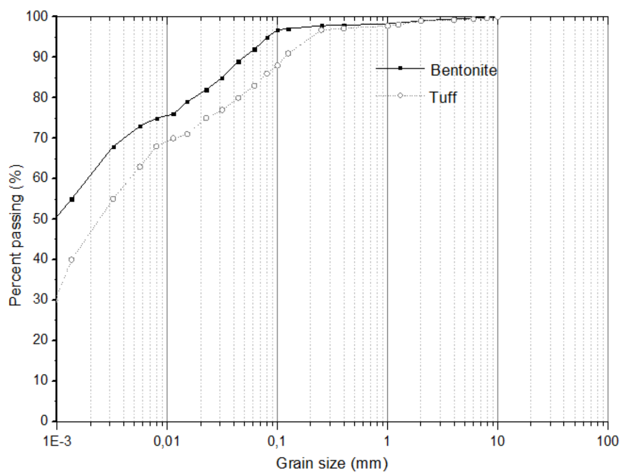

Fig. 1. Grain–size distributions for used materials.

The specific gravity of the tuff and the bentonite soils was 1.92 and 2.61, respectively. Figure 1 shows the particle size distribution of the soils. Table II shows the chemical analysis of the tuff sample according to the NF EN 1744 standard. According to the USCS soil classification system, tuff soil is defined as low-white clay. The main constituent of tuff soil was 70.25% calcite with a ratio of SiO_2/Al_2O_3 equal to 3.60. The bentonite of Maghnia is defined as a high-plasticity clay. Its main constituent was silica with 65%, with a ratio of SiO_2/Al_2O_3 equal to 3.76. Fe_2O_3, CaO, MgO, and Na_2O are high in bentonite soil.

TABLE II. CHEMICAL COMPOSITIONS OF SOILS

Property	Tuff	Bentonite	Cement
SiO_2 (%)	9.56	65	20.18
Al_2O_3 (%)	2.65	17.25	5.26
Fe_2O_3 (%)	0.58	2.10	2.91
CaO (%)	70.25	5	59.20
MgO (%)	2.61	3.10	3.05
Na_2O (%)	4.90	3.2	0.15
K_2O (%)	1.38	1.7	0.25
Loss in ignition (%)	8.09	2.65	9.0

2) *Plastic Waste Powder*

One hundred used caps of plastic water bottles were mechanically shredded at room temperature to create the used plastic fiber. Since the plastic chips were elongated particles between 1 and 10mm in length with an average of 5mm, it was impossible to determine their gradation curve as in normal aggregates. Additionally, the sample also contained plastic powder, which tended to lump together and comprised about 60% of its weight. Natural resources such as cellulose, natural gas, and crude oil can be converted to plastics using a polycondensation or polymerization process [22]. The plastic powder can be obtained by breaking and grinding waste plastic. The plastic powder has a qualitative weight of $0.93 gm/cm^3$, 0.015% water absorption, 54MPa ultimate tensile strength, and 110-450Mpa modulus of elasticity [23]. Figure 2 shows a sample of the plastic powder.

Fig. 2. Plastic waste powder

B. *Mixtures Design*

1) *Preparation of Soil-Plastic Powder Mixtures*

The samples were prepared in an optimal protector with a water content that corresponds to liquid reduction. The water content of the samples was removed by drying at 35°C. The samples were considered completely dry after 24 hours. Since the qualitative weight of the plastic powder is less than half that of the soil, the mixing rates were high, up to 25% of the plastic powder. The mixtures were prepared with 15% of the water content and were pressed in the standard proctor in five layers to ensure a uniform dry density. The assembly of samples required sitting with 1Kg due to the great difference in the qualitative gravity of the components. After soil pressure and mixtures, the uninterrupted cylindrical samples were released from the mold using a hydraulic crane. The samples were wrapped in plastic to prevent losing water.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Consistency Limits

Atterberg limit tests were performed to determine the consistency limit values of the soils and their mixtures according to the AFNOR NF P 94-051 methods. Figures 3 and 4 show the effects of plastic powder on the consistency limits of the tuff and bentonite mixtures, respectively.

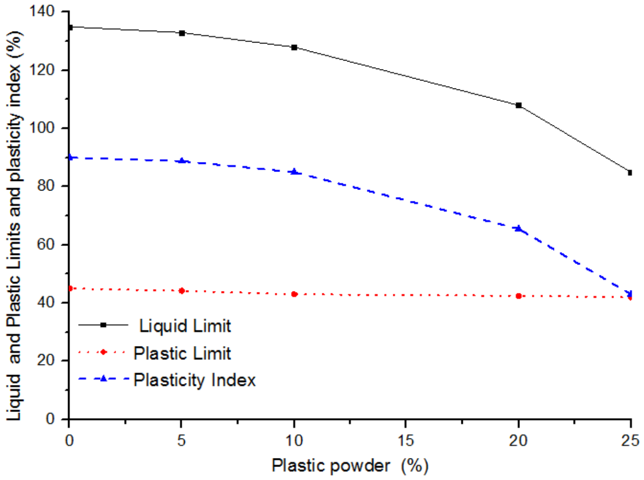

Fig. 3. Consistency limits for tuff and its mixtures.

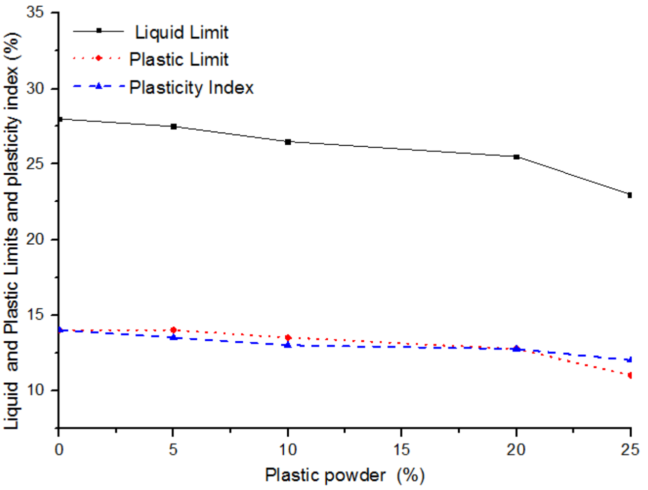

Fig. 4. Consistency limits for bentonite and its mixtures.

The liquid limits for both soils and their mixtures decreased gradually when the plastic powder content increased. The results of the Atterberg limit tests indicate that bentonite has lower plasticity than tuff soil, which makes it less susceptible to plastic powder than tuff. The kind [24], composition, cation exchange capacity, and metal content ratios of the mixtures could all contribute to changes in their plastic limits [25-27].

B. Odometer Tests

1) Swell-Consolidation Tests

Swell-consolidation tests were performed according to the AFNOR XP 94-91 standard on all compacted specimens. These tests were conducted in a conventional odometer of 50mm diameter and 20mm thickness. Since the composite samples were made as described above, the initial void ratio (*e*) varied depending on the amount of plastic powder used. The specimens were statically compacted in the odometer into five layers, each 4mm thick, to ensure uniform dry density. Heave was allowed under a seating surcharge resultant to the odometer (approximately 7.5kPa). Following the final heave (*ΔH*), the samples were compressed under increasing vertical pressure until the initial void ratio (*e*) was reached for the mixtures, as well as the swelling potential (*S percent*) and swelling pressure (*ps*). Reports on the puffs included information like the percentage increase in the thickness of the sample when submerged (*ΔH*) compared to its original thickness (*H*). The swelling pressure (*ps*) was determined as the compression of the initial vacuum ratio (*E*) of the samples obtained from the E-Log P. It is necessary to remember that the compression of the soil and the plastic powder, as well as the water in the pores, is small compared to the compression of the soil skeleton.

2) Effect of Plastic Powder Fibers on Swell Potential

Figures 5 and 6 show the variation in the swell potential (*S*) versus time for the tuff soil samples compared to the samples mixed with 5, 10, 20, and 25% plastic powder and 2.5% cement. The test results indicate that tuff soil gives a swell potential of 3.75% reached in 22 days without treatment, while bentonite gives 13.35% in 25 days without treatment. The final swelling of the samples decreases and reaches the same time for the compound samples with 5% plastic powder, and at a lesser time for samples with 10, 20, and 25%.

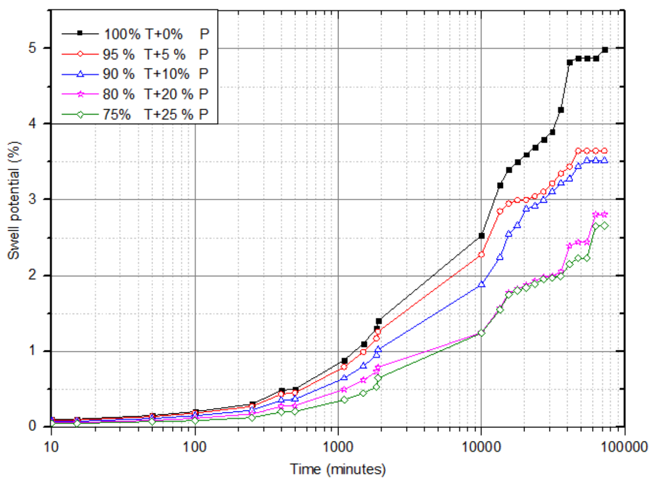

Fig. 5. Effect of the plastic powder content on the swell potential of tuff.

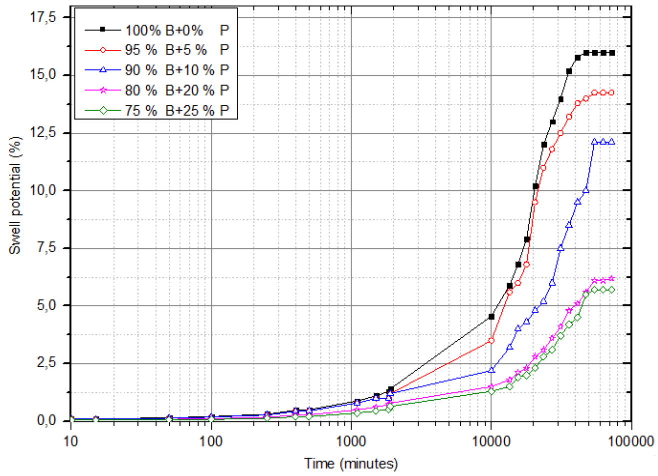

Fig. 6. Effect of the plastic powder content on the swell potential of bentonite.

It can be observed that the swell potentials of tuff and bentonite can be significantly reduced using plastic powder and low-cement (2.5%) mixtures. For the two soils, the reduction of the swell potential gradually increases with powder content. The reduction in the swell potential of tuff soil varied from 21.6% to 25.8% for mixtures with 10 and 20% powder content, respectively, and is approximately 11.7% for mixtures with 10% powder content. All samples were prepared at a 15% water content and since plastic powder absorbs at least 3% of its weight, the water-to-tuff ratio at the start of the test was about 0.11, 0.18, 0.22, and 0.26 for the samples with 0, 5, 10, 20, and 25% of plastic powder, respectively. These may be the reasons for the reduction of the reach time in achieving the maximum heave. For bentonite with 5% plastic powder, the reduction of swell potential was about 6.5% with 10% plastic powder and about 23% for the samples having more. A further reduction in the swell potential of Bentonite was obtained with increasing duration. The swell potential of bentonite with 25% plastic powder decreased to 2.25% in 12 days. This lowering of the reached time was due to the initial water-to-bentonite ratios, which were approximately 0.11 and 0.26 for samples with 0 and 25% plastic powder, respectively. The reduction in the swell potential of the mixed bentonite samples compared to pure bentonite increased gradually from 6 to 89% when the powder content increased from 5 to 25%. This was also confirmed in [28] and [29] by testing the effects of plastic powder on clay.

3) Effect of Plastic Powder on Swelling Pressure

Figures 7 and 8 show the swelling potential and swelling pressure for the tuff and bentonite specimens. Swelling pressure (*ps*) decreases with the addition of plastic waste powder. Figure 7 shows that the swelling pressure was 48kPa for the pure tuff specimens, while the swelling pressure values for the composite specimens with 5, 10, 20, and 25% plastic powder content were 46, 40, 32, and 31kPa, respectively. Figure 8 shows that the plastic powder content reduces swelling pressure in the bentonite composite. The swelling pressure for the pure bentonite specimen was 153kPa, while the swelling pressure for bentonite with plastic powder content at 5, 10, 20, and 25% were 137, 120, 118, and 117kPa, respectively. The swelling pressure values of tuff were less than half that of bentonite. The reduction in swelling pressure of the composite samples with 25% of plastic powder was approximately 30% and 54% for bentonite and tuff, respectively.

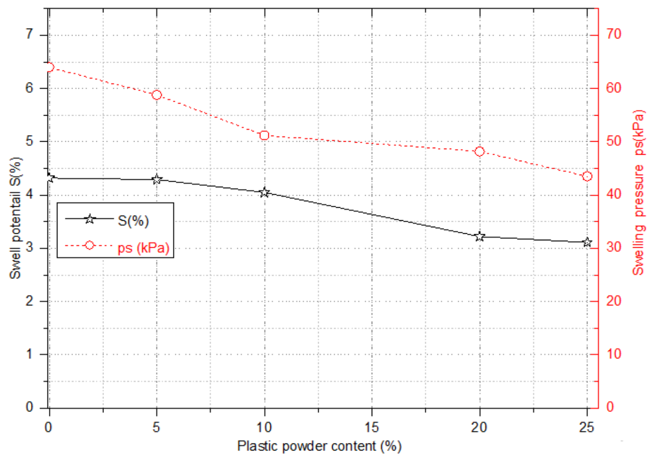

Fig. 7. Effect of plastic powder content on the swell potential and pressure of tuff soil.

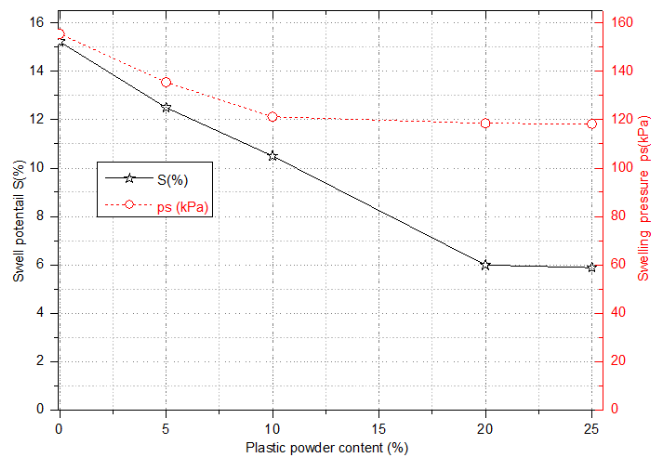

Fig. 8. Effect of plastic powder content on the swell potential and pressure of bentonite soil.

C. Loading-Unloading tests

Given that plastic powder is compressible and its specific gravity is less than half of the soil, supplementary testing was conducted following the odometer protocol conditions to obtain additional information on the mechanical behavior of the soil and its mixtures. The compression (*Cc*) and recompression indices (*Cr*) were determined according to AFNOR XP 94-090-1 for soil and composite samples.

1) Effect of Plastic Powder Compression Index

Figures 9 and 10 show the compression indices for tuff, bentonite, and their mixtures with plastic powder. It is common knowledge that compression index (*Cc*) is the semi-logarithmic fall of the linear percentage of the pressure void ratio curve.

The *Cc* values are relatively small because the remolded *Cc* is always smaller than the undisturbed ones. The values varied from 0.2491 to 0.5230 for bentonite and its mixtures, and from 0.22 to 0.403 for tuff and its mixtures. For the two soils, *Cc* gradually increases with plastic powder content. Similar results were obtained in [30] and [31].

2) *Effect of Plastic Powder Recompression Index*

Figures 9 and 10 present the recompression (swell) index and the decompression index *Cr* for tuff and bentonite soils and their mixtures with plastic powder. In general, the *Cr* values of the recompression index are approximately 5 times smaller than the compression index *Cc,* as in [32]. For all tested samples, *Cr* was about 3.5 or 4 times smaller than *Cc* and increased with plastic powder content. The values of the decompression index *Cr* ranged from 0.0829 to 0.1712 for bentonite and its mixtures and from 0.050 to 0.1480 for tuff and its mixtures.

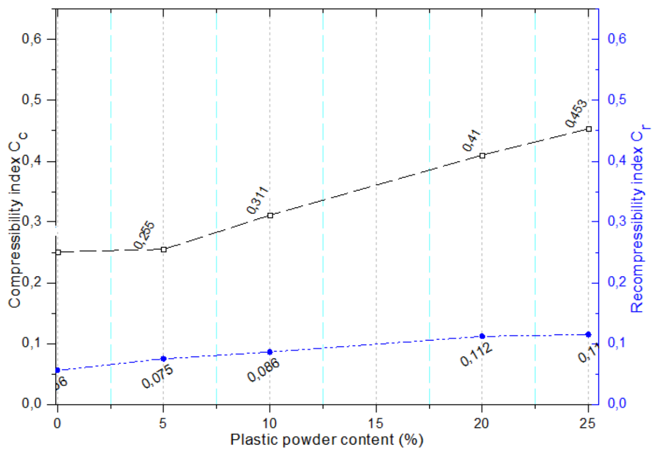

Fig. 9. Effect of plastic powder content on compression and recompression index of tuff soil.

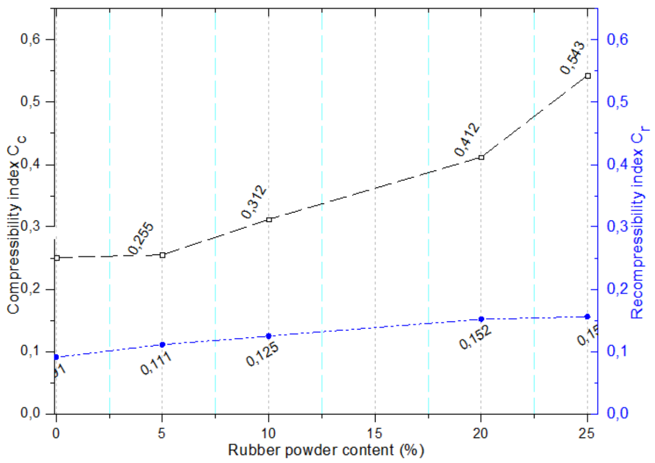

Fig. 10. Effect of the plastic powder content on compression and recompression index of bentonite

IV. CONCLUSION

Based on the experimental results, it can be concluded that mixing tuff soil with plastic powder reduces heave and swelling pressure, due to the use of plastic powder in place of swellable soils and the resistance it provides to swell when in contact with soil fibers. The reduction of swell potential for 5% plastic powder content is about 1.4 for the soils with low plasticity compared to high plasticity. For 10, 20, and 25% plastic powder content the reduction is about the same in the two clayey soils. The reduction in swelling pressure is slightly more significant for tuff soil with 10, 20, and 25% plastic powder than for bentonite soil with the same contents of plastic powder. The opposite was observed for mixtures with 10% plastic powder. Since plastic powder absorbs water at most 3.4% of its weight, composite samples reach a final heave in less time compared to pure clay. This time gradually decreases with the plastic powder content. The compression and recompression indexes gradually increase with the plastic powder content for the two clayey soils and exceed the double for 25% of plastic powder content. Plastic powder with low cement (2.5%) significantly reduces the likelihood of swelling regardless of soil elasticity, but increases the compression of the mixtures. Using plastic waste as a substitute for synthetic fibers creates a cost-effective product that protects the environment from waste, conserves natural resources, and retains mechanical qualities suitable for use in non-structural applications. Instead of using expensive synthetic fibers to support fragile soils, this initiative aims to deposit plastic waste economically and efficiently and reuse it in soils, resulting in an inexpensive but effective product for soil stabilization.

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